Water Use in Industries of the Future: Aluminum Industry[1]

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3.1 Aluminum Industry

Contributed by Jim Mavis, in CH2M HILL's Seattle, Washington, office

3.1.1 Structure of the Aluminum Industry

Overview – Mining through Recycling

Aluminum became available in commercial quantities after about 1886 with the independent discoveries of Hall and Heroult that aluminum could be produced electrolytically from a solution of alumina (aluminum oxide) in molten cryolite. The advent of commercially feasible reduction of aluminum oxide to the metal forged the essential link between mining and alumina production and metal working methods that had already been established for many other metals, in some cases in ancient times.

After nearly 120 years of evolution, the modern-day aluminum industry consists of 5 major components, as illustrated in Figure 3.1-1. The starting point is bauxite, an aluminum-rich mineral that is no longer produced in the continental United States. Bauxite is digested in sodium hydroxide, and purified aluminum oxide trihydrate ($Al_2O_3 \bullet 3H_2O$) is precipitated and calcined to alumina (Al_2O_3).

Alumina is the immediate feedstock used in the electrolytic production of aluminum metal. The segment of the domestic industry that uses the Hall-Heroult process is present in the United States, and is referred to as the "primary aluminum," the "reduction," or the "smelting" segment of the industry.

Metallic aluminum, usually as ingots (or other solid form), but sometimes in molten form, is used in the production of intermediate or finished products. This segment of the domestic aluminum industry is frequently termed the "forming" industry. Excess material trimmed during manufacturing is recycled internally or sold as scrap to recyclers.

Products circulated in the marketplace eventually exceed useful life or otherwise become

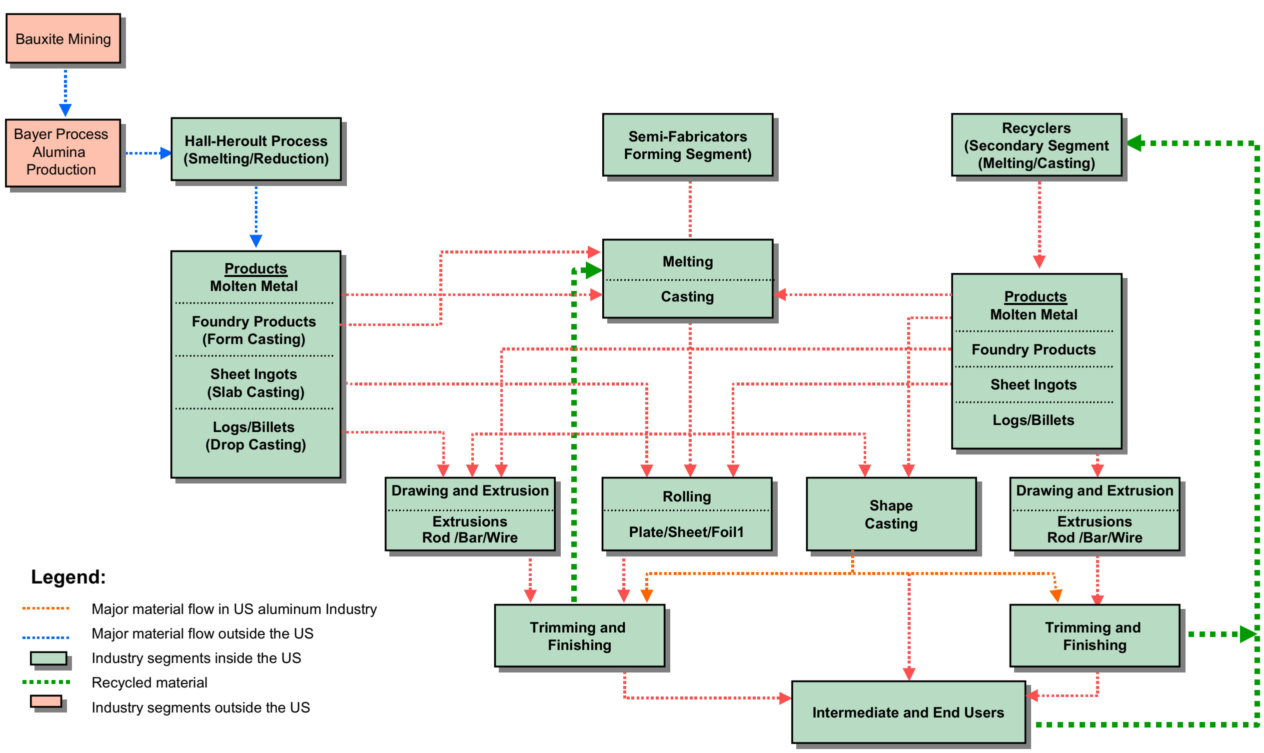

FIGURE 3.1-1
Summary of Aluminum Industry Structure in the United States

scrap. Aluminum scrap can be converted back into products at considerably lower cost than is possible when the reduction segment is involved. Over the previous 30 years, progressively larger percentages of aluminum have been reclaimed as scrap and reused as intermediate or consumer products. The aluminum recycling segment of the industry is often referred to as the “secondary aluminum” segment.

The aluminum industry in the United States consists of the reduction (Hall-Heroult) or smelting segment, the forming (intermediate or finished product fabrication) segment, and the recycling segment. Two decades ago, the lines between aluminum industry segments in the United States were more distinct than they are now. During that time, economies of scale and synergies have been exploited, blurring some features of these once-distinct segments.

Nevertheless, it is convenient to consider the smelting (Hall-Heroult reduction) segment as distinct and to consider forming along with recycling in describing aluminum industry water use characteristics.

Precursor Segments of the Domestic Aluminum Industry

Aluminum production in the United States is predicated on bauxite mining and processing. Originally, bauxite deposits in the southeastern part of the country supplied the downstream industry segments in this country. Economically recoverable bauxite deposits are no longer available in the United States and bauxite refining is now performed at only two domestic facilities.

Since the depletion of economic reserves in the United States, bauxite has been shipped into the country to feed the few remaining domestic bauxite processing plants, which use the Bayer Process to recover refined aluminum oxide from crude bauxite. Bauxite processing is often referred to as “refining.”

The Bayer plants convert the aluminum-rich mineral into aluminum oxide, the feedstock used in the smelting segment. Bayer Process plants dissolve aluminum oxide from bauxite in hot alkali, forming a crude sodium aluminate solution, while keeping insoluble iron and other metal oxides in the solids phase.

Digested liquor is separated from the insoluble solids, and aluminum oxide-trihydrate is precipitated by cooling. Other constituents are left behind. The aluminum oxide trihydrate is calcined to form aluminum oxide that can be reduced to aluminum metal in a smelter (reduction plant). The aluminum-depleted stream is recycled and regenerated with lime to form crude caustic soda to be used in the next digestion cycle.

Hall-Heroult Process (Smelting) Industry Segment

Aluminum metal is produced by electrolysis of alumina that is dissolved in molten cryolite. Reduction plants fall into two categories based on the form of the carbon anode (positive electrode).

Pre-bake plants use carbon anodes that are formed from pitch binder and petroleum coke, which is baked at high temperature to form a solid carbon block. Soderberg plants use an uncured pitch-coke blend that cures as it is heated while it slowly drops into the molten cryolite bath. The anodes are consumed during the process and have to be continuously replenished (Soderberg anodes) or replaced (prebake anodes).

A simplified schematic of a pre-bake plant is shown in Figure 3.1-2. Aluminum oxide (alumina/ore) is stored on site in silos and some of it is used in fluid bed contactors to adsorb fluoride from the electrolytic cells (“pots”) and to adsorb hydrocarbons from the anode bake furnaces. The fluoride- and hydrocarbon-enriched alumina is fed into the pots along with virgin alumina. The pots resemble steel tubs—steel shells lined with thermal insulating material.

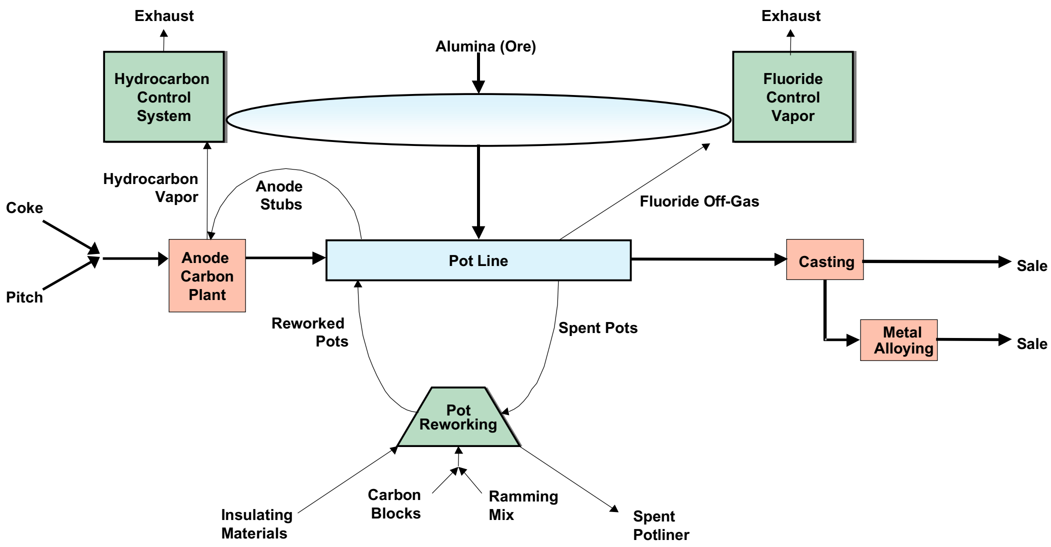

FIGURE 3.1-2
Schematic of a Pre-Bake Aluminum Smelter

For purposes of water use, the forming segment is divided into three major subcategories based on the types of operations used in processing the metal: drawing and extrusion, rolling, and shape casting. Other classifications are also used, such as end use vs. intermediate products, or type of end use, such as beverage containers. Figure 3.1-1 shows the forming segment in relation to the other aluminum industry segments.

Inside the refractory layer is a lining of carbon blocks, which act as the cathode (negative electrode for the electrolytic reaction) that is in contact with molten cryolite.

In the pots, alumina is electrolytically converted to aluminum metal (reduction) in the pots, and to carbon dioxide and monoxide at the anodes. The cryolite is unaffected by the electrical current, making it necessary to replenish only the aluminum oxide as it is converted into metal. The metal remains molten until it is removed for casting or other uses. (Some aluminum users accept molten metal instead of cast ingot or cast shapes, provided they are close enough to a producer of molten metal.)

Water is not used directly in the reduction of alumina to aluminum metal. It is used only in casting of the molten metal into the various smelter products. Common products from a reduction plant are regular ingots (pigs and sows), sheet ingots, tees, logs, and billets.

Semi-Fabrication (Forming) Industry Segment

The forming industry is very diverse, compared to the refining and smelting industry segments.

Facilities that perform drawing and extrusion operations typically combine those operations with numerous other ancillary processes to produce intermediate or finished products. Drawing and extrusion are performed with lubricants to prevent galling. These lubricants are removed by various cleaning processes prior to further manufacturing steps, such as surface finishing or assembly. Manufacturing wastes may include scraps from trimming the aluminum parts to the correct size tolerances. Scrap metal might be recycled back to on-site melt furnaces, or sold to commercial recyclers.

Rolling mills produce aluminum sheet or foil, whether for sale as an intermediate product or for packaging and sale to end users. Irregular edges are trimmed and sent to recycling facilities. As with drawing and extrusion, rolling may be performed with organic lubricants. Rolled aluminum stock may be cleaned and it is often coated for protection against damage during storage, shipping, and handling.

Aluminum casting and forging may accompany other forming operations at a semi-fabrication facility. The source of aluminum may be ingots, or in some cases, molten metal sold “over-the-fence.” Depending on the intended end use, cast aluminum parts may undergo surface finishing, may be machined to final tolerances, or may be otherwise processed before final assembly or sale. Scrap aluminum can usually be returned to the melting furnace for on-site reuse.

Recycling Industry Segment

Aluminum recycling has grown rapidly over the past 10 to 20 years, with improved efficiency in collecting scrap metal from end users of retail products and from commercial sources. Many recyclers use aluminum scrap in manufacture of their own products, significantly blurring the once-distinct lines between recycling and the rest of the aluminum industry.

Scrap aluminum may be remelted and alloyed to meet intermediate product specifications of purchasers who buy ingot or molten metal. By production of ingots, sheet ingots, foundry products, logs, or billets, the recycling segment of the aluminum industry duplicates certain operations that are also characteristic of the smelting segment. And by producing various cast shapes, rolled intermediates, and finished products such as beverage cans, the recycling segment overlaps with the forming segment. The extent to which the recycling segment overlaps with the smelting and forming segments is indicated in Figure 3.1-1.

3.1.2 Water Use by Industry Segment

The discussion of water use in the domestic aluminum industry focuses on smelting (primary or reduction), forming (semi-fabrication) and recycling, since these are the main segments currently represented in the United States. A very brief discussion of bauxite refining is also included here, since it represents such a small fraction of the domestic aluminum industry.

Information about the smelting segment came from several sources, but mainly from a combination of public documents (EPA, 1986) pertaining to water use and wastewater discharge permits and permit applications, and from industry experts. Similarly, information about water use in the forming segment was abstracted from about 20 wastewater discharge permits and other contact with the industry.

Much of the available information emphasized wastewater quantity and quality because of the focus on environmental issues over the past 30 years. Actual water use practices were either taken from facility water balance diagrams or were estimated from information about water uses within the plants.

The water uses and production-normalized usage rates were taken for plants or systems in which reasonable water conservation measures were in place. Once-through water systems were not included in the water use compilation discussed in the following subsections. Selection of the most water-efficient examples does not imply that site-specific issues do not warrant once through or low-recycle water uses. The selection was based on a desire to identify typical water demands for specific operations within each industry segment.

Bauxite Refining

Digesting bauxite and extraction of alumina is a water- and chemical-intensive process. High-value sodium hydroxide (caustic soda) is added to an aqueous slurry of bauxite and heated to dissolve aluminum as sodium aluminate. Aluminum oxide trihydrate precipitates when the digestion solution cools, leaving impurities and some of the caustic behind.

The caustic is expensive, so Bayer plants recycle water that has residual caustic, in order to optimize economic performance of the bauxite refinery. In practice, virtually all water that is added to the process is recycled (only in high rainfall areas does surplus water accumulate). Usage varies, but estimates from published accounts indicate that about 450 gallons of water are used per ton of bauxite processed (Aughinish Aluminia, www.aughinish.com; Solymar et al., 1997; TMS, 1997).

Hall-Heroult Process (Reduction Segment)

Water is not used directly in the Hall-Heroult process (reduction of alumina to aluminum metal), but is essential as cooling water for casting ingots, logs, tees, and other solid products. Water is also an important resource for the aluminum smelting industry in the Pacific Northwest and Upstate New York where, until the recent energy crisis, it was the source of low-cost hydroelectric power.

Water uses and quantities used in aluminum smelting are summarized in Figure 3.1-3. Although not used in the reduction process, cooling water is essential in metal casting operations in the smelting segment. Together, direct contact and non-contact cooling comprise about 44 percent of the water use in the smelting segment of the aluminum industry, used in roughly equal amounts.

Non-contact cooling water is used to some extent for cooling molds, melt furnace doors, and other devices, and is typically low in environmental contaminants. Direct contact cooling is sprayed directly onto logs, tees, and other shapes as they are being drop-cast, and typically contains suspended solids, oils, and other possible impurities. Non-contact cooling water can be reused through reduction of its temperature in a cooling tower, or by cascade reuse in other processes. Direct contact cooling water reuse normally involves oil and particulate removal, and temperature reduction in a cooling tower.

Drop casts require short, high volume flows of cool water. Because of the high instantaneous flow rates used for drop casting, a cooling tower with its limited cold-side reservoir capacity usually cannot supply enough water for these bursts. The common practice is to supplement recirculating cooling water with cool, raw water, thereby using a greater volume of water than if there were large cold water reservoir from which to draw.

The next largest water use in aluminum smelting is non-contact rectifier cooling. Rectifiers convert thousands of amperes of alternating current into direct current, which is used to electrochemically reduce aluminum oxide to the metal, plus keep the pots hot enough to maintain cryolite in its molten state. About 23 percent of the water used in the aluminum smelting segment is used for rectifier cooling (Figure 3.1-3). Rectifier cooling water is warm but is otherwise not contaminated, making it suitable for on-site reuse in other operations such as makeup to wet air pollution control systems.

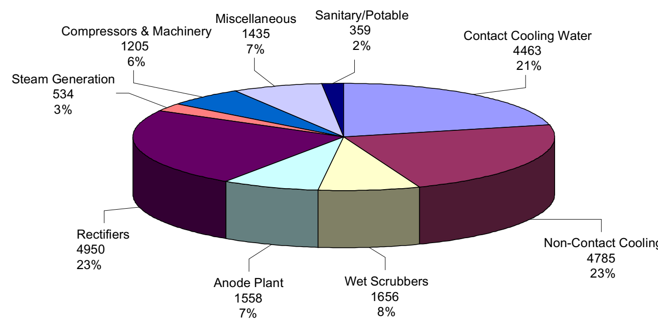

FIGURE 3.1-3
Water Consumption: Gallons per Ton of Primary Aluminum

Each of the next three largest water consuming operations in aluminum smelting uses about one-third the amount of the three already described. Wet air pollution control devices (scrubbers) consume about 8 percent of the water used in a reduction plant; anode production (pre-bake plant) consumes another 7 percent; and miscellaneous uses take another 7 percent.

Wet scrubbers do not necessarily require good quality water, and often are supplied with wastewater from other areas in the plant. Consequently, wet scrubbers should not be viewed as imposing *additional* demand for fresh water resources, unless too little wastewater is available to supply the air pollution devices, or if aerosol formation restricts use of wastewater in air pollution control devices. It is noteworthy that poor quality makeup can result in deposition of mineral scale inside the pollution control systems, creating operating and maintenance problems.

The demand for water in baked anode production varies among plants. In some facilities, water does not come into contact with the anodes, whereas in others, anodes may be spray-cooled. Miscellaneous water uses also vary widely among plants in the aluminum smelting segment, and generalization would be difficult. Basically, miscellaneous uses are those not accounted for after all known significant and minor uses have been identified.

Only small quantities of water are used for cooling machinery and compressors, for boiler makeup, and for sanitary consumption. Compressors and machinery uses comprise approximately 5.7 percent of water used in a "typical" aluminum smelter, while boilers consume another 2.5 percent and sanitary consumption constitutes only 1.7 percent of the water used.

Semi-Fabrication (Forming) Segment

The structure of the forming segment of the aluminum industry sharply contrasts with that of the aluminum smelting segment. Aluminum smelters are based on one fundamental process (electrochemical reduction of refined bauxite) and produce a limited number of products (ingots, specialized castings, and molten metal). The forming segment employs numerous manufacturing processes, many not represented in the majority of the forming facilities, and produces a wide variety of intermediate and final products, in contrast to the aluminum smelting segment.

Water consumption in the highly diversified forming segment is described in the following discussion in terms of individual manufacturing (core) operations and ancillary operations. Water consumption is expressed as volume of water used per ton of finished product. Figure 3.1-4 summarizes water usage for the core and ancillary operations in aluminum forming. The list of operations is indicative of the aluminum-forming segment, but is not exhaustive because of the diverse nature of the segment. Some data for the use categories overlap, but the information was used as received (confidential sources within industry), because insufficient detail was available to support further analysis.

As for the smelting segment, there was a wide range of water usage per ton of finished product reported. Data based on once-through cooling and abnormally low-cycle reuse (i.e., low-cycle cooling towers) were removed, and the remaining water use rates were averaged for incorporation into Figure 3.1-4.

Figure 3.1-4 indicates more than a 50-fold range of average water usage per ton of finished product. Throughout the following text, cases in which averages are strongly biased because of unusually high water consumption in one facility are identified. The water uses in Figure 3.1-4 are grouped according to the subcategories in Figure 3.1-1.

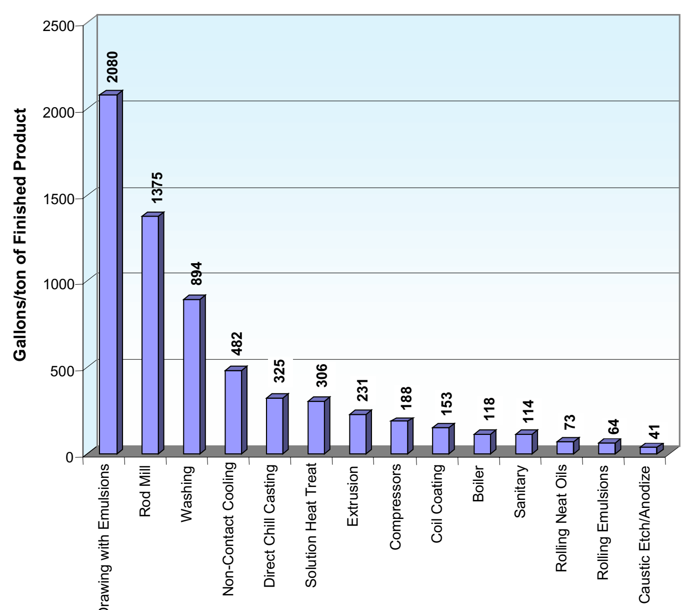

FIGURE 3.1-4
Water Usage in Various Aluminum Forming Operations (Source: Data compiled from confidential CH2M HILL HILL clients)

Shape Casting Operations

Cast aluminum may be cooled with a combination of non-contact and direct contact (direct chill) cooling water. Based on a use-per-ton of finished product, the direct chill cooling water rate averaged about 325 gallons/ton of finished product, based on information from two facilities (91 and 558 gallons/ton, respectively). In addition, non-contact cooling water may be used to cool molds and other equipment, including utilities. Non-contact cooling water at the single facility for which data were available was about 482 gallons per ton of finished product. Cooling water is usually recycled through cooling towers to reduce the volume of effluent that must be discharged. The heat removed during casting cooling is dissipated as "low-grade" heat from the evaporative cooling towers.

Water use in the single rod mill for which data were available was about 1,375 gallons per ton of finished product.

Drawing and Extrusion Operations

Drawing (with emulsions) consumed the largest *average* volume of water of all the operations for which information was available—nearly 2,100 gallons per ton of finished product, based on information from three facilities with flow rates ranging from 170 to 5,900 gallons per ton. This usage rate was strongly biased by a single source that consumed nearly 6,000 gallons of water per finished ton of product. The other two facilities reported consumption rates of 170 to 190 gallons per ton of finished product.

Water use in aluminum extrusion averaged about 230 gallons per ton of finished product (data were from two plants), with over a 6-fold range in the consumption rate between the lowest and highest usage rates (the range was 64 to 397 gallons per ton).

Rolling

Rolling with emulsions consumed an average of 64 gallons per ton of finished product, based on data from three facilities. The range of water consumption rates spanned a factor of 2, with a low rate of 35 gallons per ton and a high rate of 71 gallons per ton.

Rolling with neat oil (oil with no water) had an average water consumption of 73 gallons per ton of finished product. The data were taken from two facilities. Individual water consumption rates were 29 gallons per ton and 118 gallons per ton, respectively.

Solution Heat Treating

Solution heat treating used contact cooling water to quench heated aluminum. Two facilities reporting water consumption for heat-treating consumed an average of 306 gallons per ton of aluminum, more than a 4.5-fold range from lowest to highest rate (111 and 500 gallons per ton, respectively). As with other cooling operations, water normally is recycled through cooling towers to reduce the volume of wastewater that must be discharged. Heat that is picked up by cooling the metal is dissipated to the atmosphere as "low-grade" heat from the evaporative cooling towers.

Caustic Etch and Anodizing

Facilities reporting water consumption for caustic etch or anodizing operations used an average of 40.8 gallons per ton of aluminum, ranging from 22.3 gallons per ton to 78 gallons per ton. Data were available from three plants.

Washing

Water consumption for washing operations from 5 facilities averaged 894 gallons per ton of product, but the average was highly skewed by a single consumption rate of 3,970 gallons per ton. Omitting the outlying consumption rate, the wash water rate ranged from 14 gallons per ton to 188 gallons per ton, averaging 125 gallons per ton.

Coil Coating

Only two plants reported coil coating, but the average for those two was 153 gallons per ton of aluminum product, with a twofold range in consumption rates (100 and 207 gallons per ton, respectively).

Boilers

Boilers consumed an average of 118 gallons per ton of aluminum, based on data from three plants. The range was 21.1 to 214 gallons per ton.

Compressor Cooling

A single plant broke out compressor cooling. Its water consumption rate was 188 gallons per ton of aluminum product.

Recycling Segment

Recycling of aluminum is economically attractive because it uses only about 10 percent of the energy that is needed to convert alumina to aluminum metal[1]. Taking into account other cost factors, the overall cost for recycling is about half the cost of producing virgin aluminum.

Recycled scrap is melted, and may be re-alloyed and held in furnaces for use in casting or for delivery of molten metal delivery to other processors. Whether the recycled aluminum is used in-house or is sent to off-site processors, the water consumption rates are reflected in the preceding section on the forming segment. Consequently, water use patterns discussed in previous subsections are not repeated here.

3.1.3 Relationship of Water to Energy

Historically there has been a strong association between the aluminum smelting industry segment and water through use of low-cost hydroelectric power to operate the Hall-Heroult reduction cells. Smelting plants near Niagara Falls and in the Pacific Northwest supplied electricity at a cost that made these regions prominent suppliers of aluminum metal.

Until the power supply situation on the West Coast in the winter of 2000 and 2001, smelters in the Pacific Northwest supplied about 40 percent of the nation’s aluminum. During the crisis, Northwest smelters shut down completely, solidifying the cryolite in the pots, and making startup unlikely for most of the facilities.

A possible outgrowth of limitations (mainly cost) of electricity is on-site electrical generation. Long-term contracts for natural gas supply are needed to make this a viable, and some of the Northwest plants would not restart, without assurances of long-term supplies of affordable electricity.

Renewable energy sources have been mentioned as an alternative to low cost hydroelectric power, particularly windmills, photovoltaic and solar thermal systems. At present these alternatives cannot compete economically with established current energy sources, and there are no renewable energy projects to supply power to an aluminum smelter. Fuel cells have also been mentioned as a promising technology. Technical advancement into direct use with hydrocarbon fuels and more favorable economics may make this option viable in the future.

Besides hydroelectric power, there is another relationship between water and energy. In smelting, forming and recycling aluminum industry segments, cooling water is used extensively to cool aluminum being processed. The rate of cooling is closely controlled to give metal products the qualities needed for their end uses, so both temperature and flow rate are important considerations in production. (Hence, although large amounts of heat energy are transferred to the cooling water when aluminum is processed, the wastewater from these facilities must be maintained at such a low temperature to maintain metal product quality that energy recovery is economically infeasible.)

[1] Anchorage Recycling Center: a Smurfit-Stone Recycling Company, www.anchoragerecycling.com, indicates 95 percent energy savings; additional energy is for collection, handling, forming, and distribution.

3.1.4 Water Reduction and Reuse Practices and Challenges

As shown previously, most water used in the aluminum industry is for solidifying molten metal or cooling hot metal. Over the past 25 years, many plants have reduced water use in response to economic and regulatory incentives related to the environment.

Water conservation measures consist of a sequence of steps, such as eliminating water use where possible, reusing non-contact cooling water in other plant operations where practical, and reducing water consumption to a large extent by installing cooling towers, changing manufacturing practices, and numerous other means. In conserving water, there is a balance between flow reduction by recycling water and the resulting concentration of constituents to the point that they become contaminants, and therefore regulated in plant discharge. Hence, in many cases, continued increases in water recycling would eventually alter a “water problem” into a “dissolved solids problem.”

Metal surface treatment may be a better candidate for water use reductions than recycling cooling water through evaporative cooling towers. The main incentive for addressing surface treatment operations differs from the familiar concern over water conservation. Surface treatment chemicals (anodizing, pickling, conversion coatings, and related intermediates or finishes) are often expensive, and if they can be recovered cost effectively from spent baths, the aluminum industry and its suppliers have strong motivation to work out technical and economic problems. Under this approach, the water used to prepare surface finishing baths would not be needed, because the bath would be “rejuvenated” by removing contaminants that make the bath ineffective, and by supplementing constituents that are lost during routine operation. This area of technical innovation has been in development for over two decades and significant technical challenges remain.

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